Hadron Collider Physics

(Lecture I)

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Outline

- Standard model issues
- Collider & detector basics
- Physics examples
- Near future

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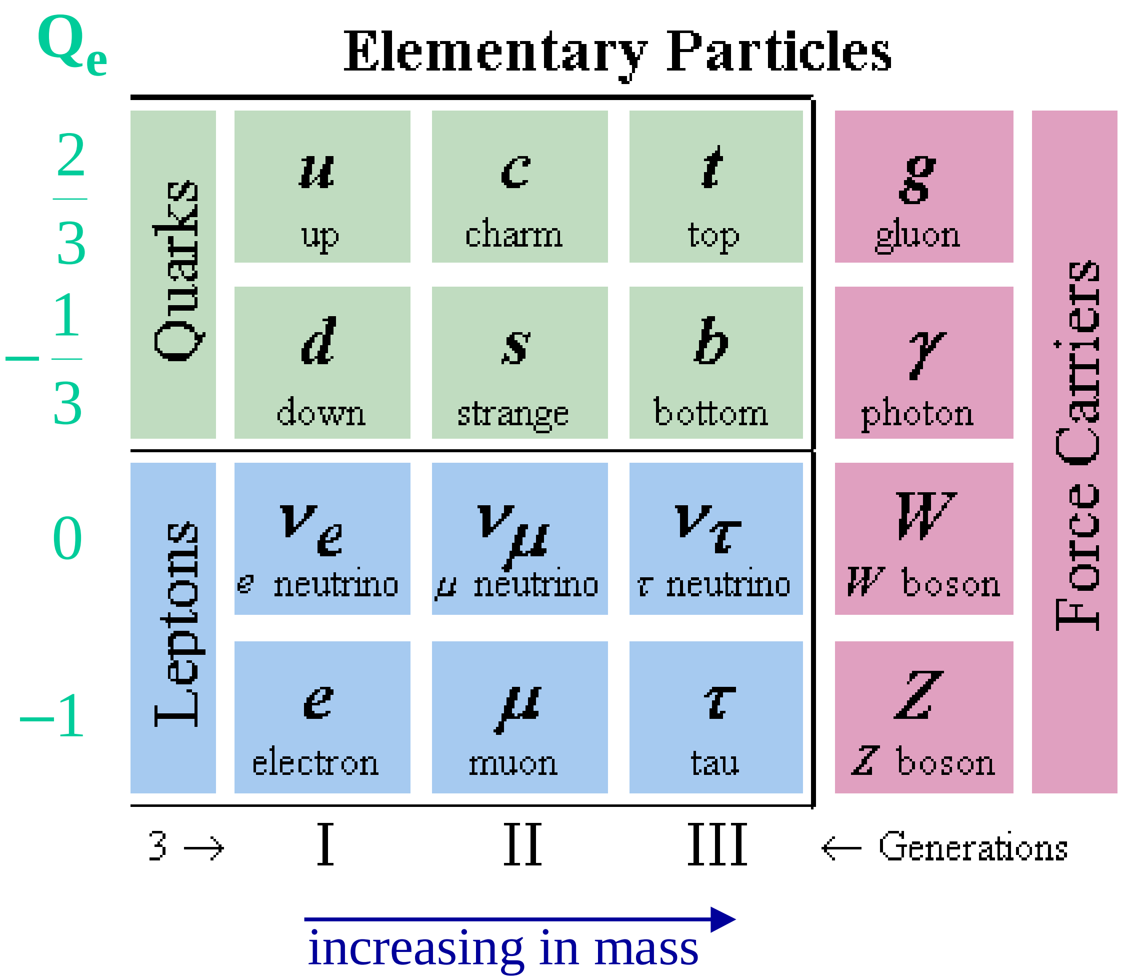
Standard Model

The Standard Model is the theory describing the interactions (strong, electromagnetic and weak) among elementary particles

Elementary particles come in two varieties
Fermions (quarks & leptons) and Gauge Bosons



The electroweak symmetry requires particles to be massless ⇒ must be broken

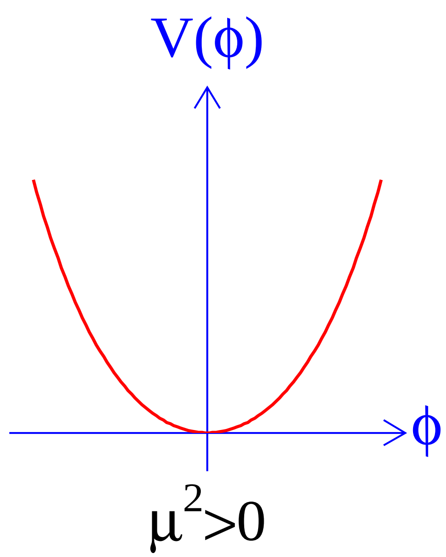
SM is a gauge theory with symmetry groups
$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$

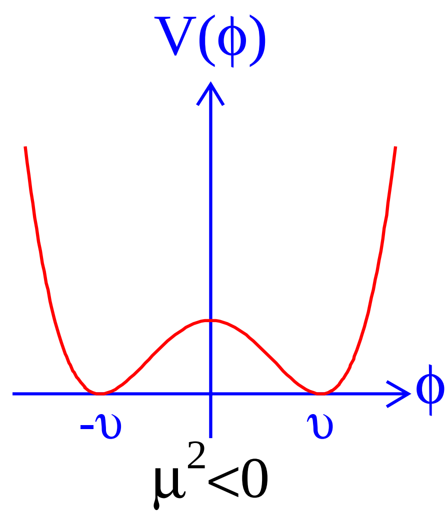
Electroweak Symmetry Breaking

The electroweak symmetry is postulated to be broken through the Higgs mechanism

Consider a complex scalar field ϕ with potential

$$V(\phi) = \mu^2(\phi^+\phi) + |\lambda|(\phi^+\phi)^2$$





The ground state does not possess the symmetry of the Lagrangian if $\mu^2<0$

Consequences of EW symmetry breaking

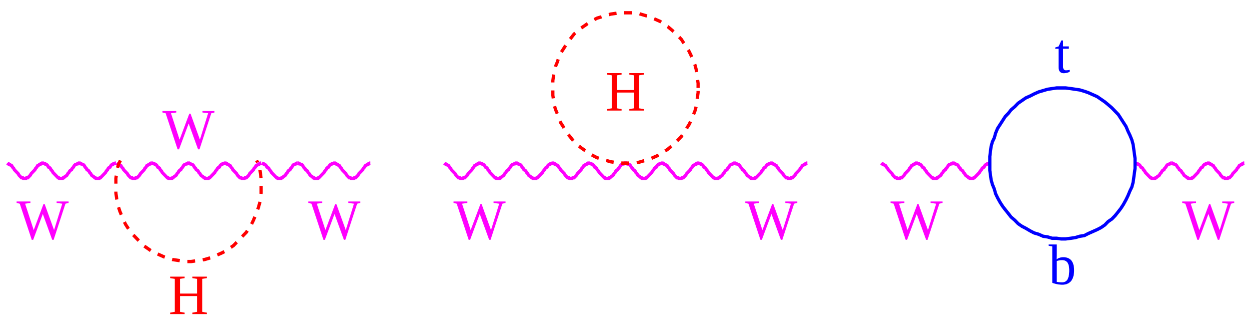
- **The mediators of weak interactions ($W^\pm$ and Z) acquire masses.**
- **Electromagnetism is mediated by massless photon.**
- **At least one massive neutral scalar particle (Higgs particle) appears, but its mass is not predicted.**
- **Fermions can acquire mass through their Yukawa couplings to the Higgs.**

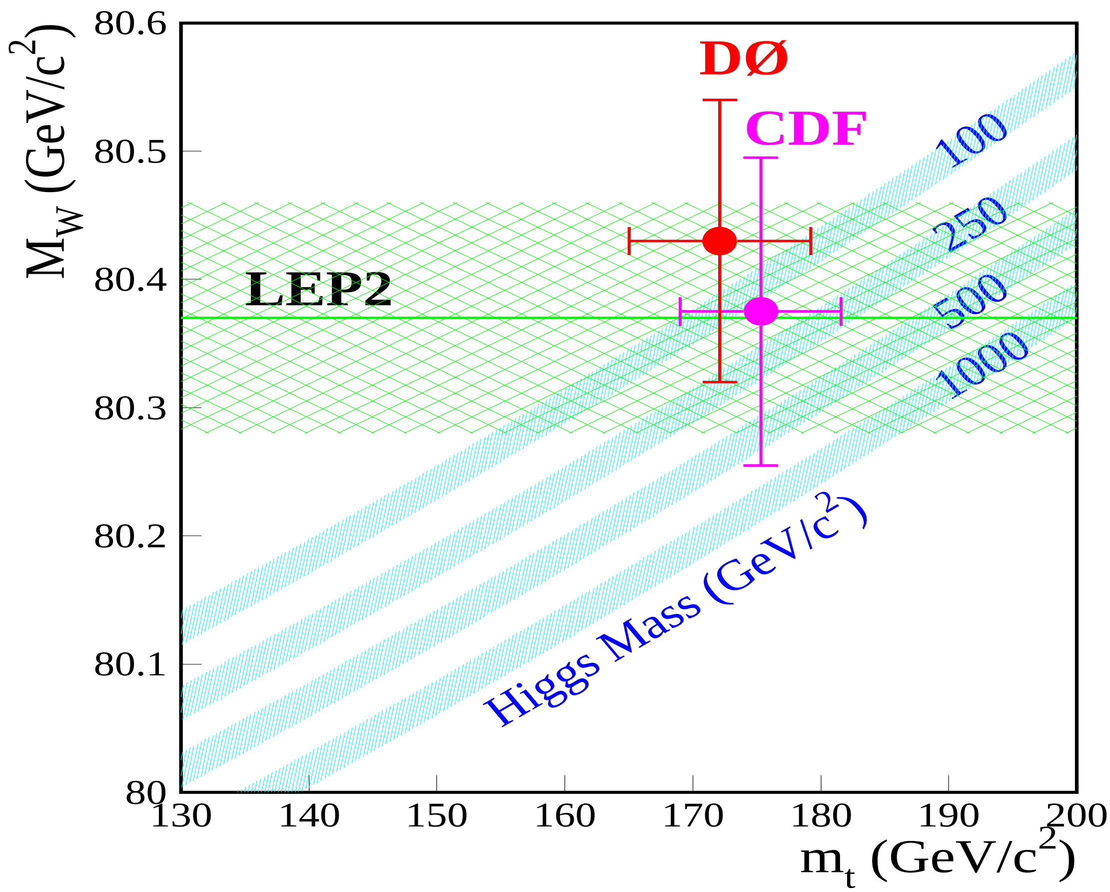
Electroweak Corrections

Within the Standard Model

$$M_W^2 = M_Z^2(1-\sin^2\theta_W)(1+\Delta\rho)$$

Radiative correction $\Delta\rho = \Delta\rho(m_t, M_H, \alpha, \ldots)$

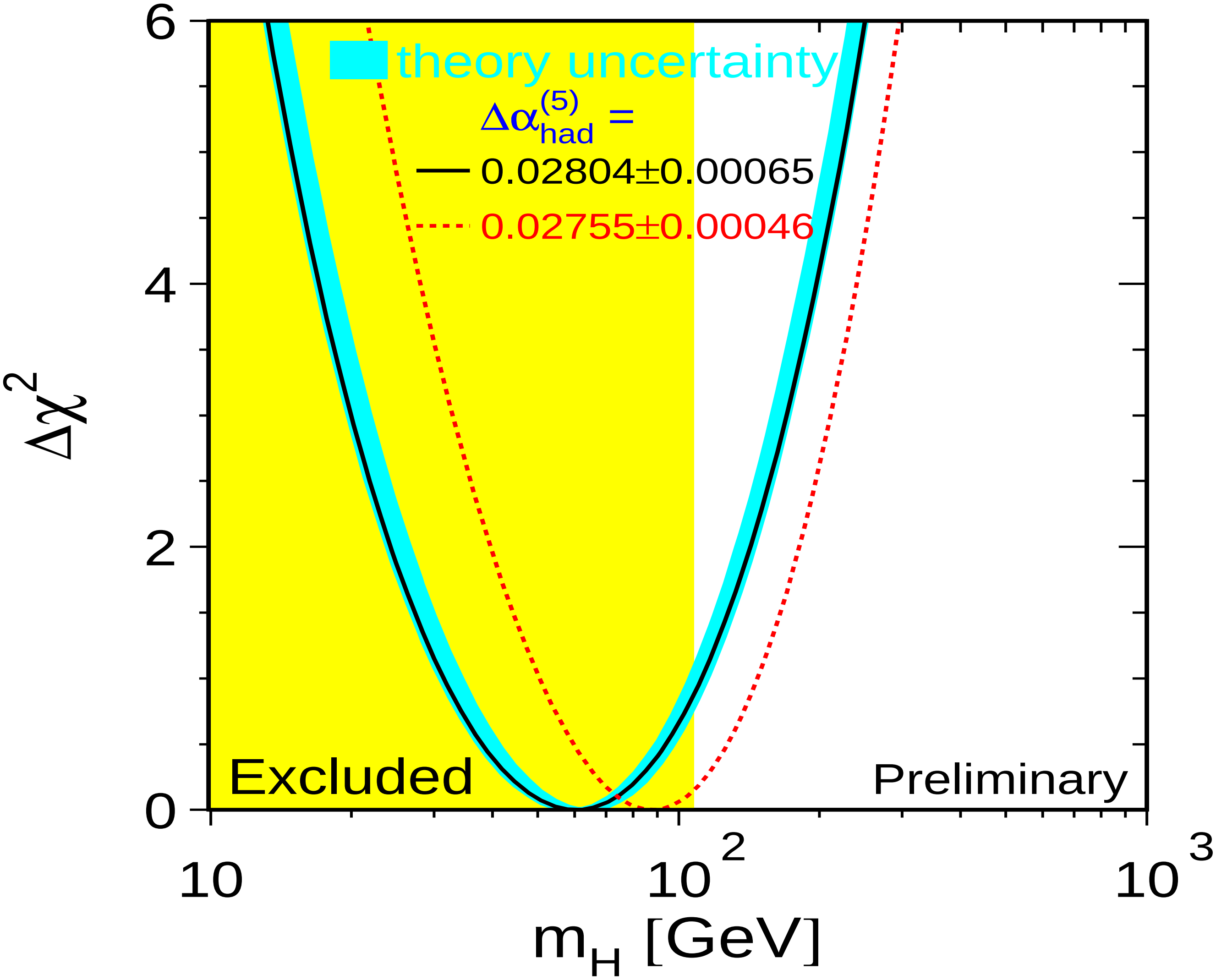




By measuring top quark and W boson masses precisely, the Higgs boson mass can be extracted

Electroweak Fit

Global fit to all precision data
(LEP, SLC, Tevatron, ...)
with Higgs boson mass as the free parameter



The fit prefers a low mass Higgs !

Direct searches at LEP exclude m_H<~114 GeV/c^2
and are suggestive for a 115 GeV/c^2 Higgs!

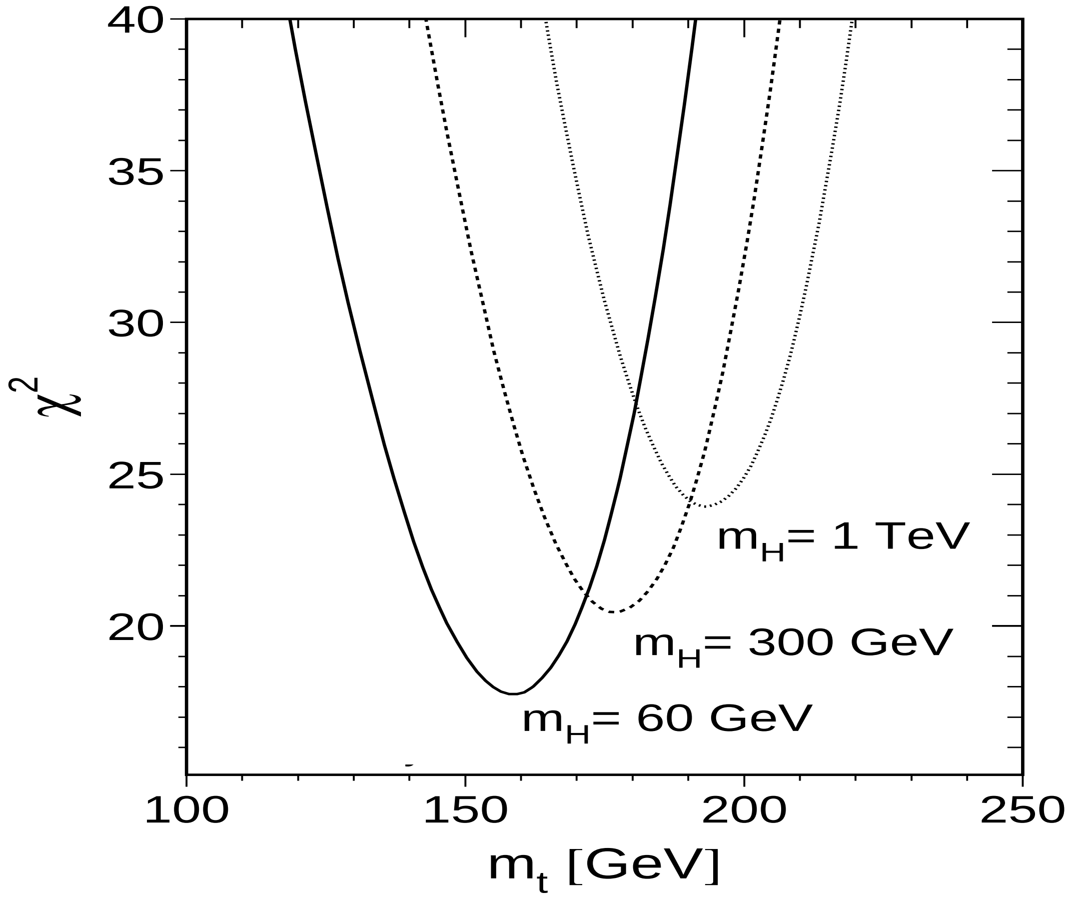
Top Mass from SM Fit

Before the top quark discovery, the top quark mass was inferred from the precision data to be

$$m_t = 177 \pm 11 \pm 19 \ \text{GeV}/c^2$$

(B. Jacobsen, XXIXth Rencontre de Moriond, 1994)

To be compared with the direct measurements of CDF/DØ: m_t=174.3±3.2±4.0 GeV/c^2



(JQ, Ph.D. Thesis, MIT, 1990)
m_t=125±35±20 GeV/c^2

Open Questions

Though there are no confirmed data that deviate from the Standard Model, nevertheless there are many open questions within the model

Top Quark

- why it is so heavy? is it special?
- does it play a role in electroweak symmetry breaking?

Higgs Mechanism

- is Mr. Peter Higgs right?
- how many Higgs fields?
- what is the origin of electroweak symmetry breaking?
- how do Fermions acquire mass?

Bottom Quark

- is CP violated in b-quark decays?

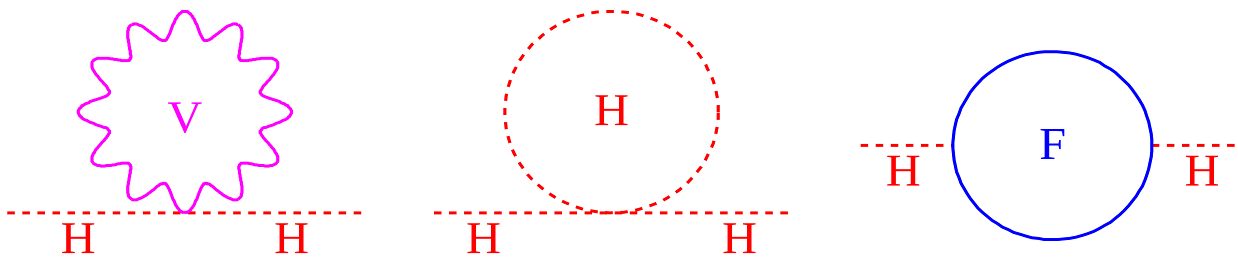
Neutrinos

- despite of recent breakthroughs, the neutrino sector is poorly understood

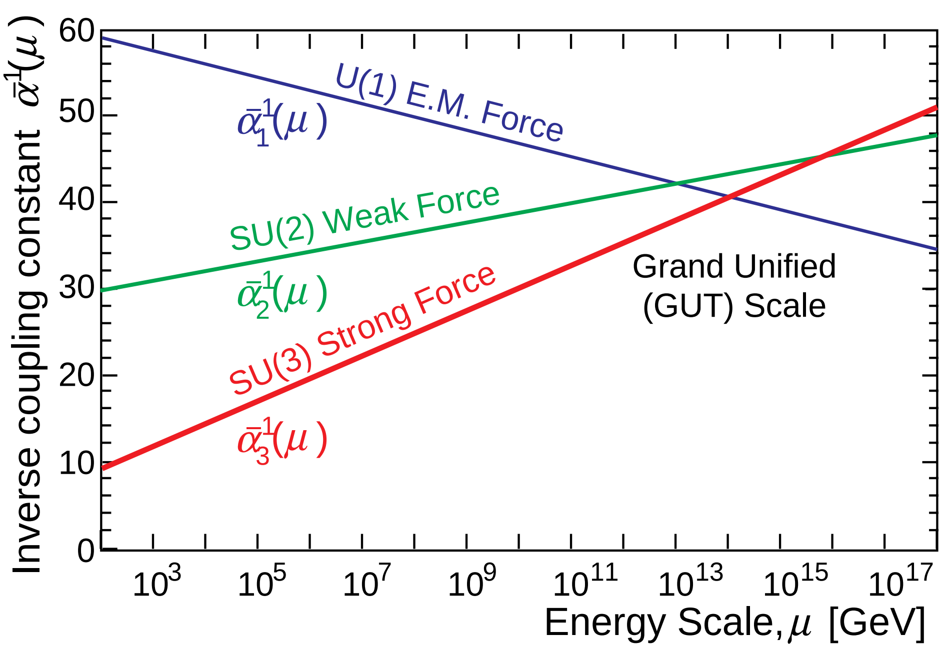
Theoretical Issues

Theoretically, the standard model is unlikely to be a complete theory

Higgs boson mass receives radiative corrections which are quadratically divergent

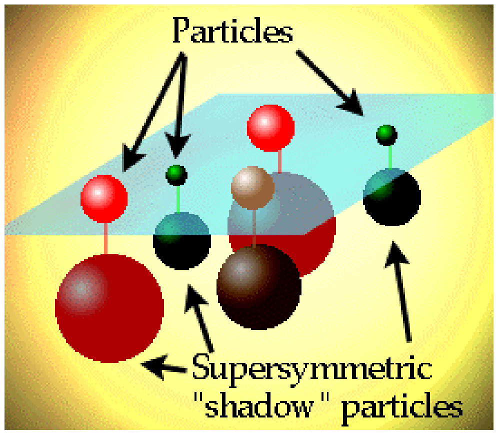


Not only standard model does not incorporate gravity, strong, electromagnetic and weak interactions do not unify at high energies without new physics

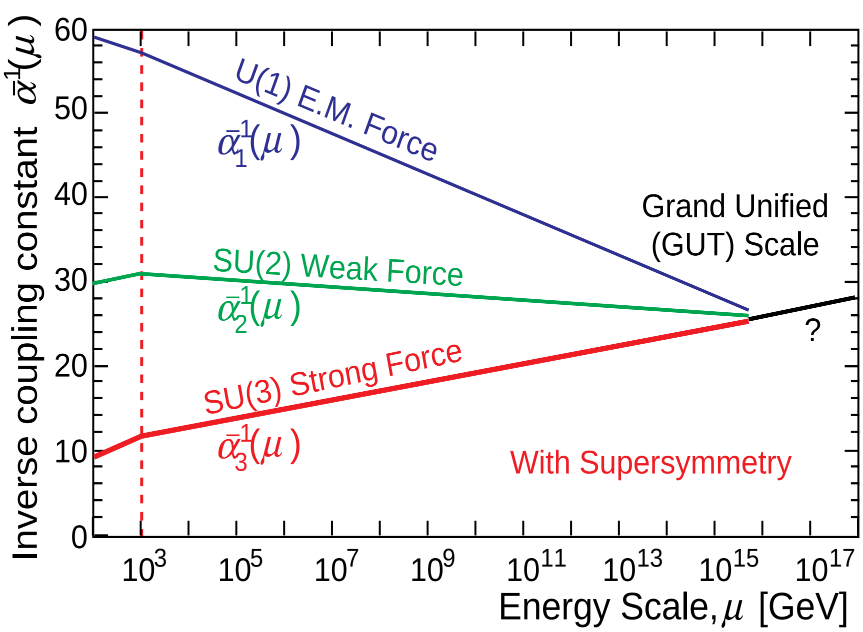


Beyond the Standard Model

Supersymmetry is a theory that theoretically popular but experimentally unconfirmed



- **It provides a solution to Higgs mass problem by equalizing numbers of fermions and bosons**
- **It offers a path to the incorporation of gravity**
- **Strong, electromagnetic and weak forces unify at high energies with supersymmetry**



Supersymmetry

To supersymmetrize the standard model, two Higgs doublets are needed which leads to five Higgs particles

Standard Model Particles

$W^{\pm} H^{\pm}$ γ Z h H A u d e ν ......

$\Downarrow$ $\Downarrow$ $\Downarrow$

$\tilde{\chi}_2^{\pm}$ $\tilde{\chi}_1^{\pm}$ $\tilde{\chi}_4^{0}$ $\tilde{\chi}_3^{0}$ $\tilde{\chi}_2^{0}$ $\tilde{\chi}_1^{0}$ $\tilde{u}_L$ $\tilde{d}_L$ $\tilde{e}_L$ $\tilde{\nu}_L$ $\tilde{u}_R$ $\tilde{d}_R$ $\tilde{e}_R$ $\tilde{\nu}_R$ ......

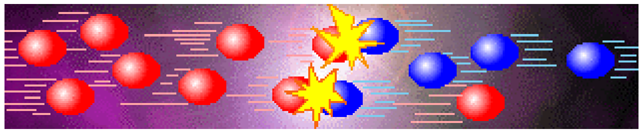
Supersymmetric Particles

Most supersymmetry models assume that R-parity (R=+1 for the SM particles and R=–1 for their partners) is conserved

1) supersymmetric particles are pair produced
2) heavy sparticles decay to lighter sparticles
3) the Lightest Supersymmetric Particle (LSP) is stable
$\Rightarrow$ missing transverse energy ($\not{E}_T$)

Events with large missing E_T are expected from the production of supersymmetric particles

Hadron Collider Chronicle

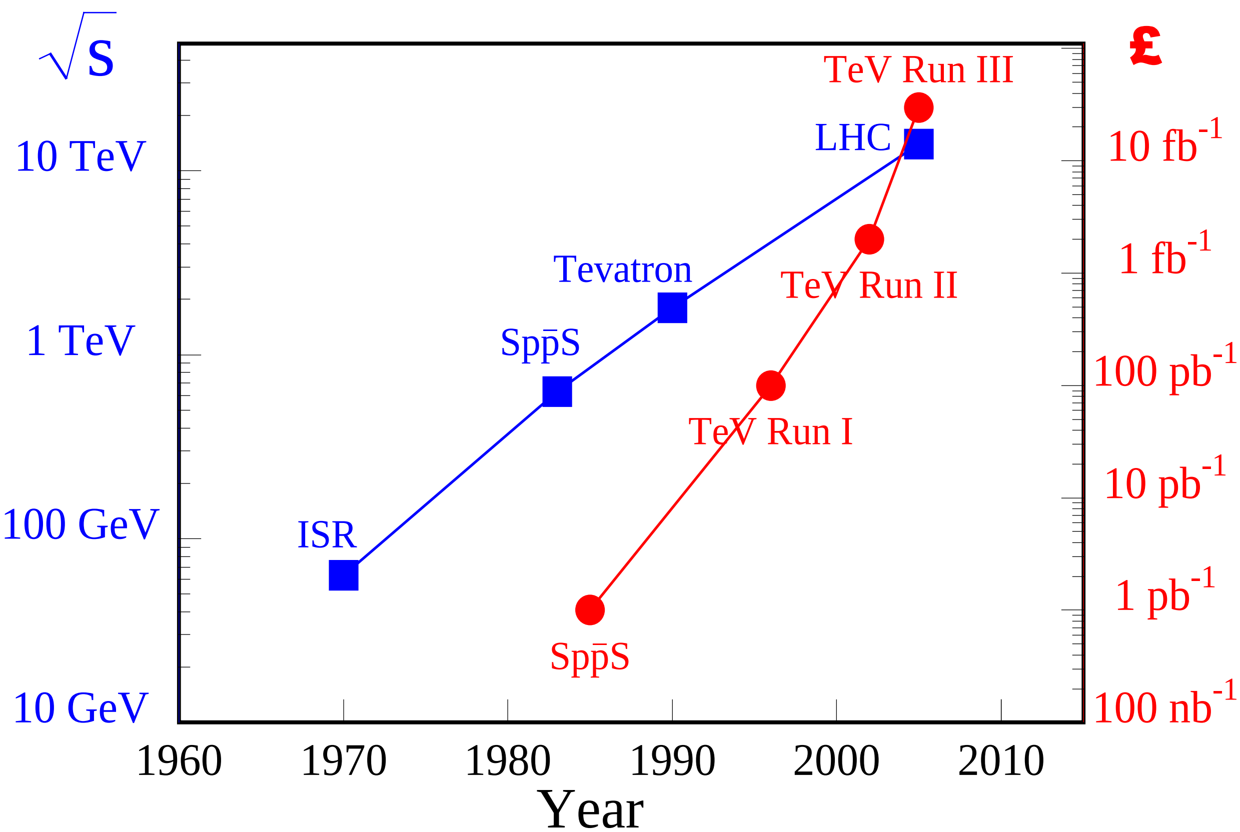
p  $\bar{p}$ (p)

Two most important parameters

Center-of-mass energy ($\sqrt{s}$) and luminosity (£)

# of events =

Luminosity × Cross Section × Efficiency = £ × $\sigma(\sqrt{s})$ × ε

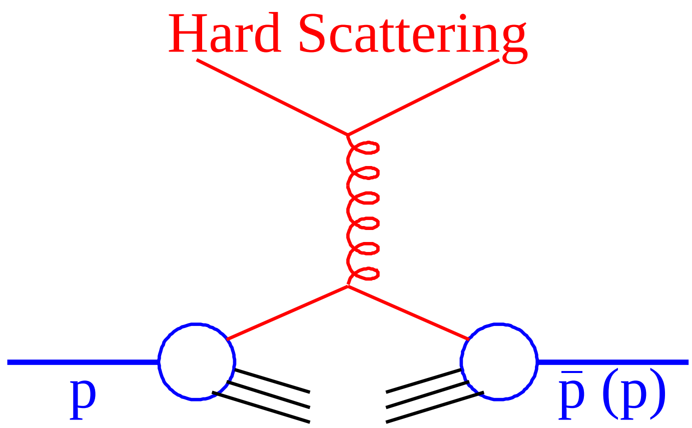


1970 : ISR at CERN	pp	high p_T physics
1982 : Sp$\bar{p}$S at CERN	p$\bar{p}$	W/Z discoveries
1990 : Tevatron at Fermilab	p$\bar{p}$	top discovery...
2005 : LHC at CERN	pp	???

Collision Kinematics

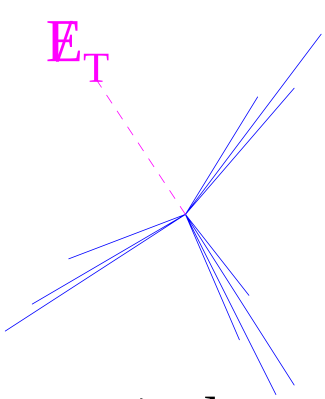
Protons (anti-protons) are composite particles

**For the purpose of hard scattering,
a proton (anti-proton) is a broad-band, unselected beam
of quarks, anti-quarks and gluons.**



**Total energy is unknown
Total longitudinal momentum is unknown
Total transverse momentum is zero**

**The total transverse energy of invisible particles
can be inferred from visible particles**



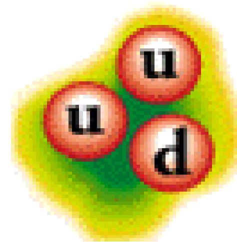
R-ϕ plane

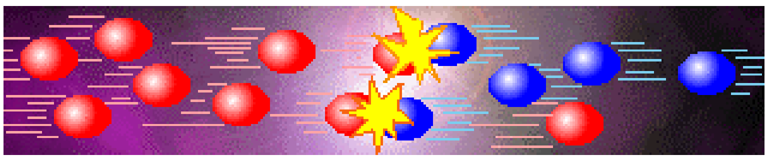
$$\sum_{\text{inv}}\vec{E}_T + \sum_{\text{vis}}\vec{E}_T = 0$$

$$\vec{\not{E}}_T \equiv \sum_{\text{inv}}\vec{E}_T = -\sum_{\text{vis}}\vec{E}_T$$

Structure Functions

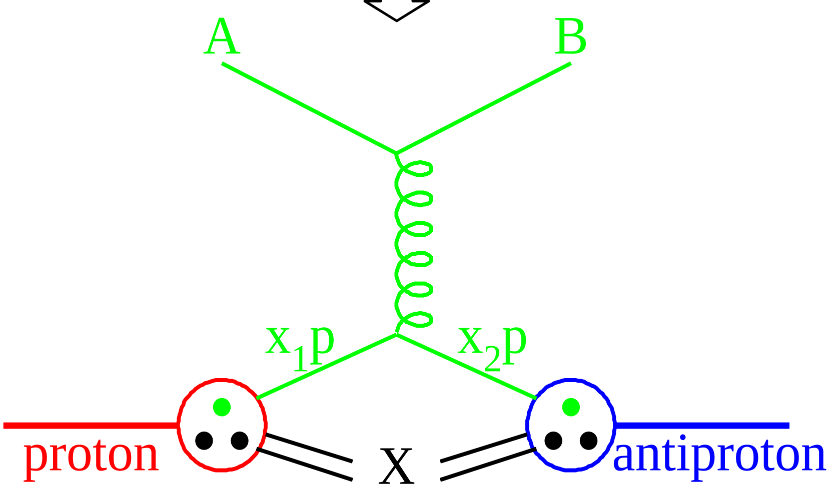
Protons are composite particles





$$p\bar{p} \rightarrow AB + X$$

$$\Downarrow$$



$$q\bar{q}' \rightarrow AB$$

parton cross section

$$\hat{\sigma}_{q\bar{q}'\rightarrow AB}(\sqrt{x_1 x_2 s})$$

Total Cross Section

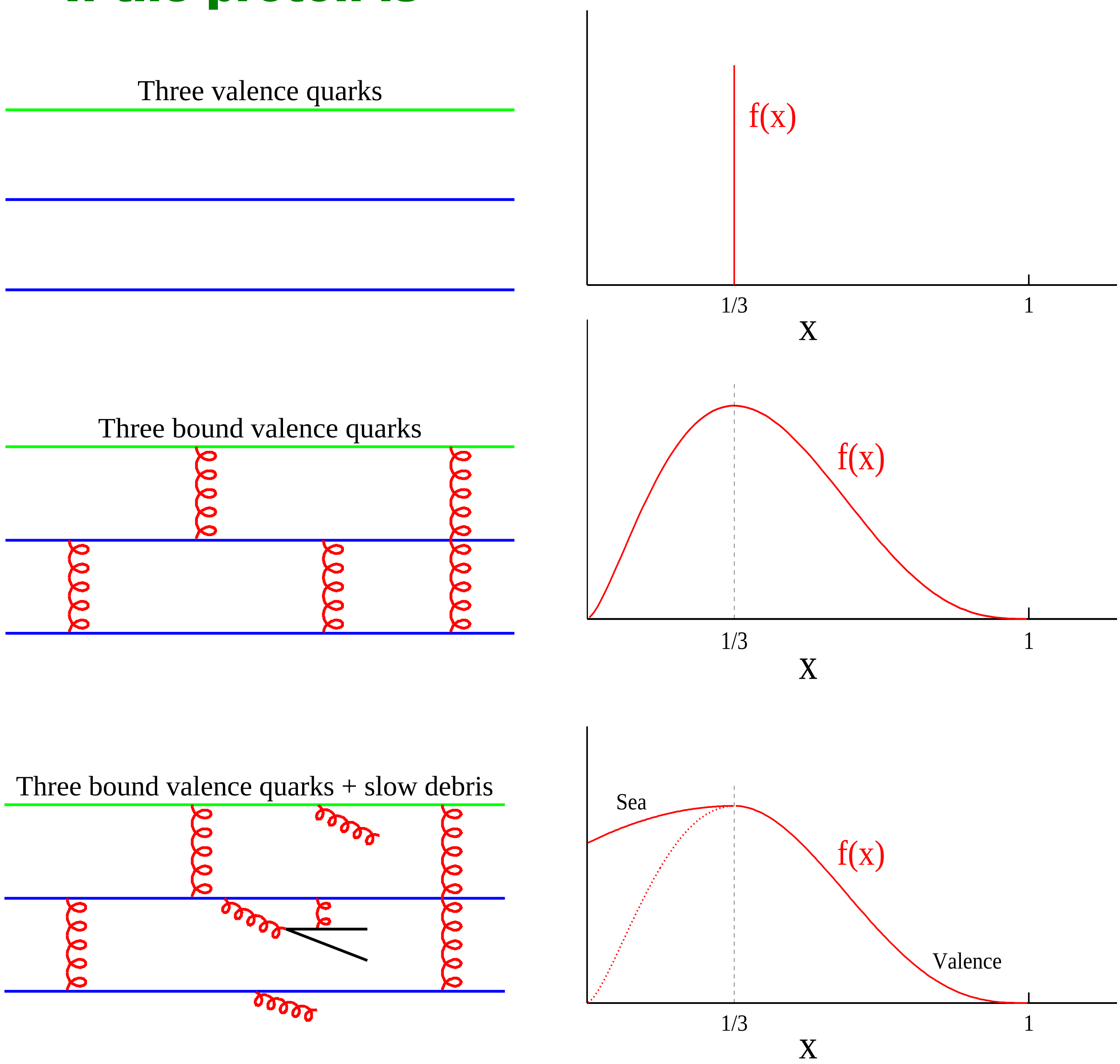
$$\iint dx_1 dx_2\, f_{q/p}(x_1)\, f_{\bar{q}'/\bar{p}}(x_2)\, \hat{\sigma}_{q\bar{q}'\rightarrow AB}(\sqrt{x_1 x_2 s})$$

$f(x)$: **Structure function**
the probability that a parton (quark or gluon) carries x-fraction of the momentum of the parent particle

Proton Structure

If the proton is

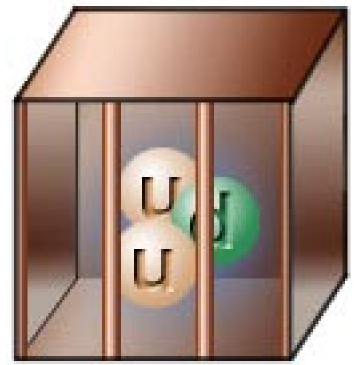
then f(x) is



About 50% of the proton momentum is carried by gluons!

Hadronization

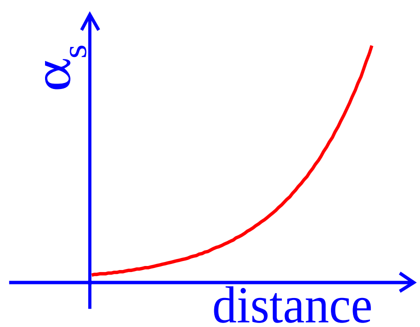
No free quarks or gluons have ever been observed color charges are confined



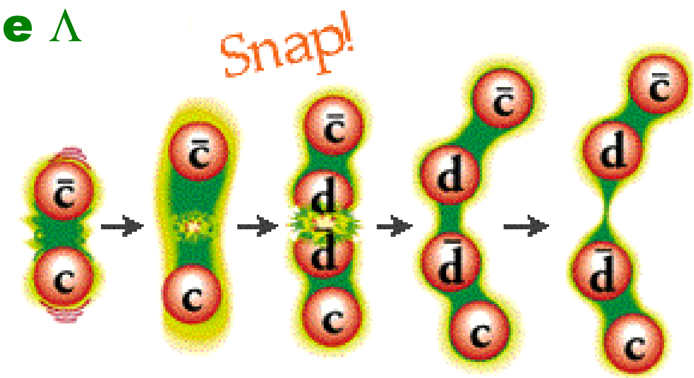
At large distance, the coupling constant becomes large

$$\alpha_s(Q^2) = \frac{12\pi}{(33-2n_f)\log(Q^2/\Lambda^2)}$$

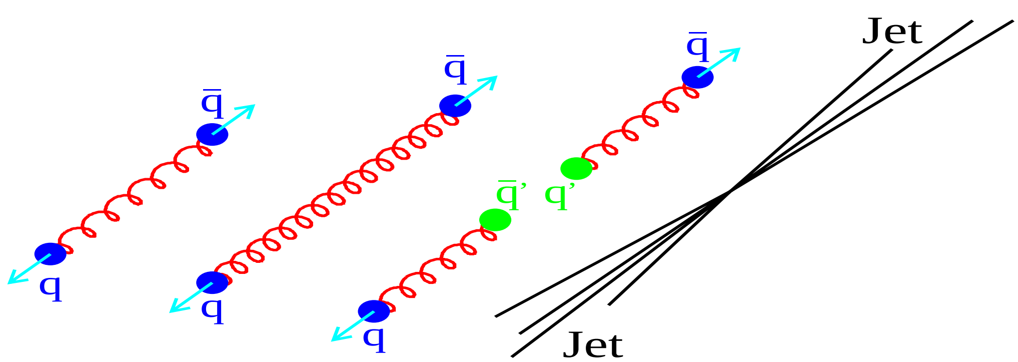
$$\Lambda \sim 200 \text{ MeV}$$



Quarks and gluons arrange themselves into strongly bound hadrons at an energy scale Λ



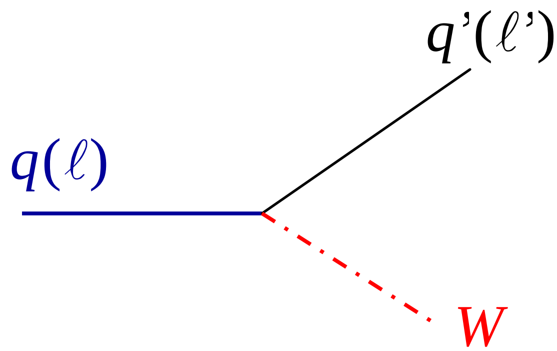
Energetic quarks or gluons fragment into streams of colorless hadrons



Particle Decay

Heavy quarks/leptons are unstable and decay via weak interaction to their lighter counterparts whenever kinematically accessible

2/3	u	c	t
–1/3	d	s	b
0	ν_e	ν_μ	ν_τ
–1	e	μ	τ



$$m_{q(\ell)} < M_W \qquad \Gamma \sim m_{q(\ell)}^5$$
$$m_{q(\ell)} > M_W \qquad \Gamma \sim m_{q(\ell)}^3$$

$$\Gamma_t >> \Lambda$$
$$\Gamma_q << \Lambda$$

With the exception of the top quark all other quarks hadronize before decay

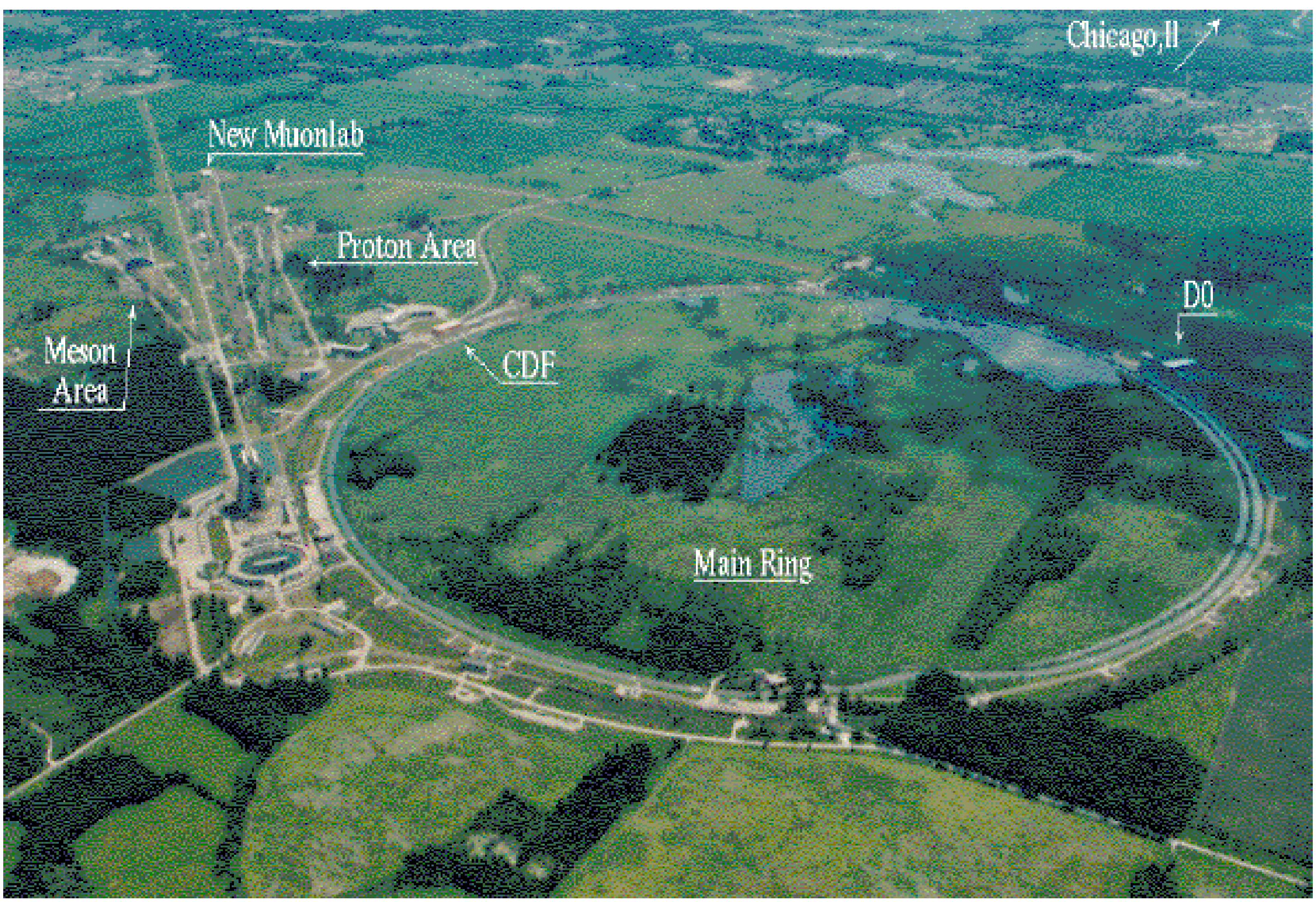
$t \to bW$	$c\tau \sim 1$ fm	**prompt decay**
$b \to cW^*$	$c\tau \sim 500\ \mu$m	**secondary vertex**
$\tau \to \nu_\tau W^*$	$c\tau \sim 100\ \mu$m	**secondary vertex**
$\mu \to \nu_\mu W^*$	$c\tau \sim 600$ m	**decay outside detector**

Tevatron Collider

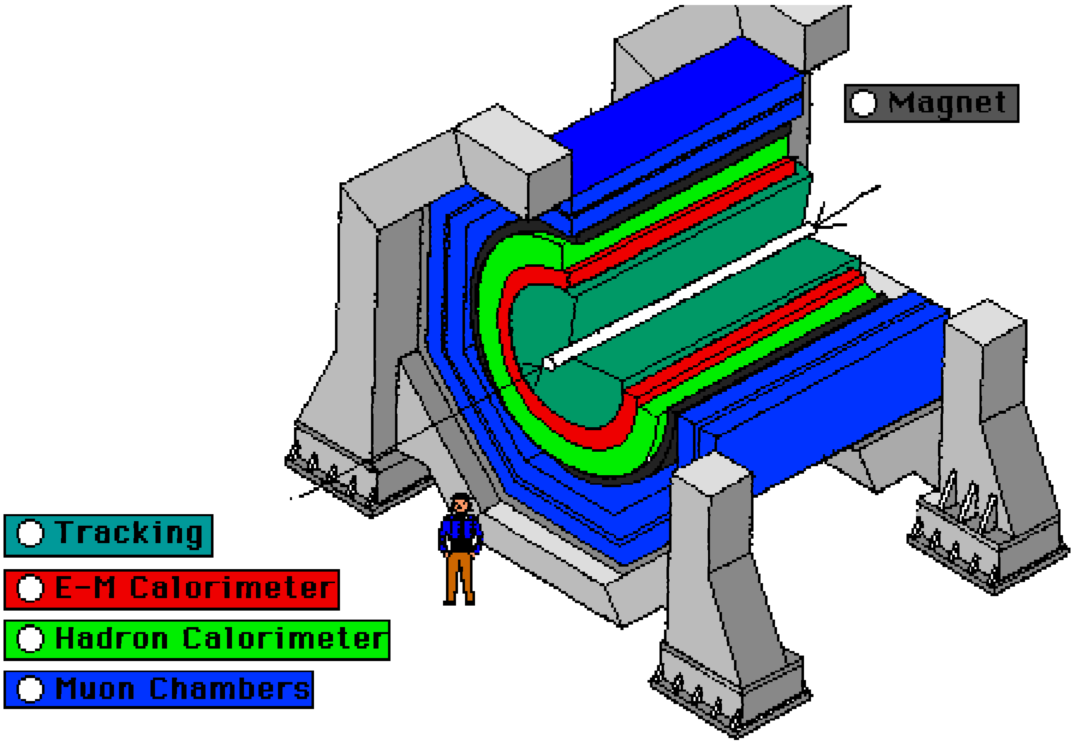
Fermilab Tevatron Collider is the highest energy collider currently in operation in the world

Proton and anti-proton beams were accelerated to 900 GeV each and were brought to collide at 2 interaction points (CDF and DØ)

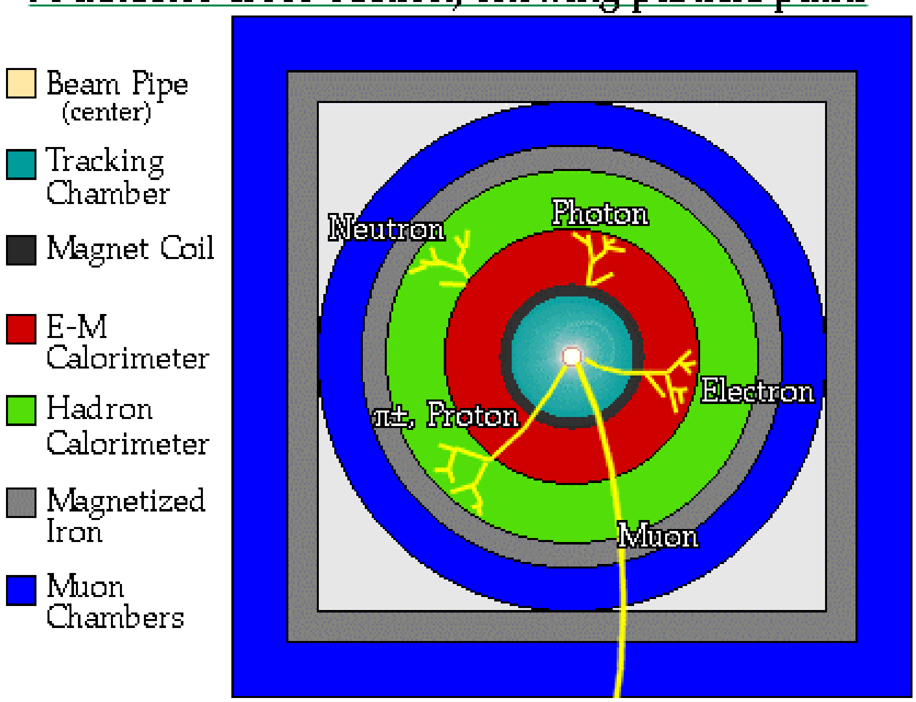
Run I (1990-1996)
An integrated luminosity of about 120 pb^{-1} was recorded per detector



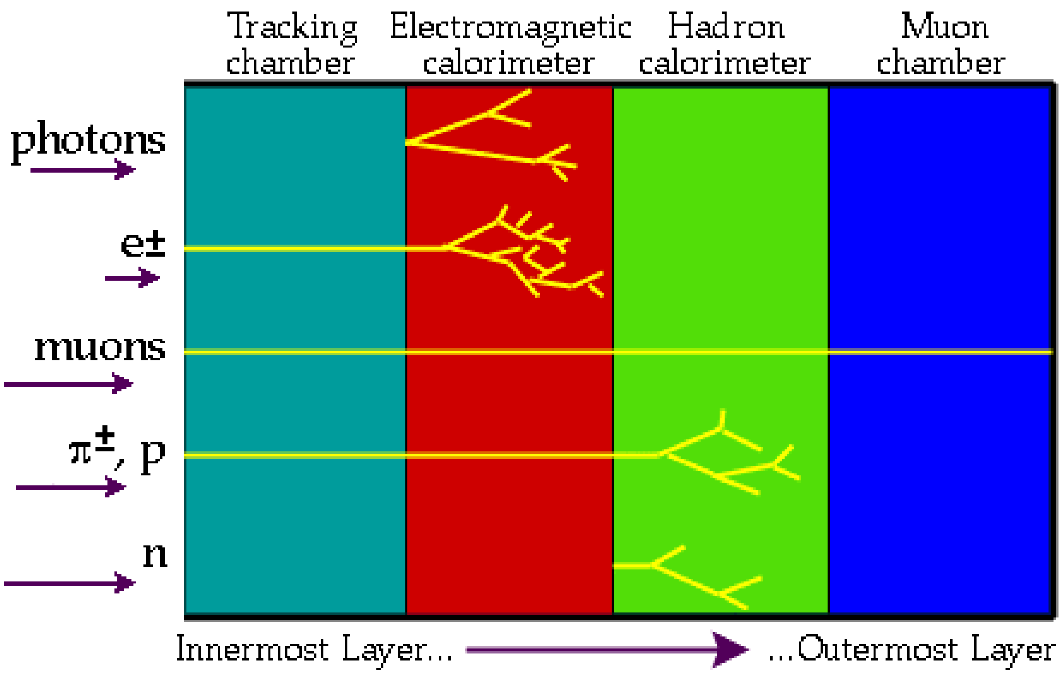
Collider Detector



A detector cross-section, showing particle paths



Particle Identification



Identified objects:

- Photons, Electrons, Muons
- Jets, b-quark jets
- Transverse momentum imbalance

EM calorimeter resolutions

$$\frac{\sigma}{E} \approx \frac{15\%}{\sqrt{E}} \quad \Rightarrow \quad \frac{\sigma}{E} \approx 2\% \ @ \ E = 50 \ GeV$$

Hadron calorimeter Resolutions

$$\frac{\sigma}{E} \approx \frac{80\%}{\sqrt{E}} \quad \Rightarrow \quad \frac{\sigma}{E} \approx 10\% \ @ \ E = 50 \ GeV$$

Tracking resolutions

$$\frac{\sigma}{p} \approx 0.2\% \times p \ \Rightarrow \ \frac{\sigma}{p} \approx 10\% \quad @ \ p = 50 \ GeV$$

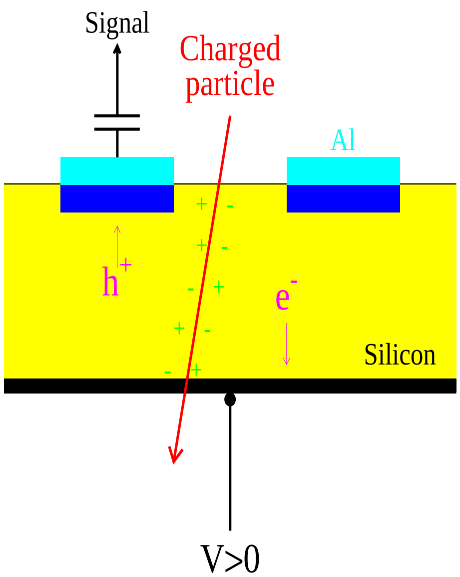
CDF and DØ Detectors

- central detector
  - magnet
  - silicon strips
  - drift chamber
- calorimeter
  - scintillator (central)
  - gas (forward)
- muon detector

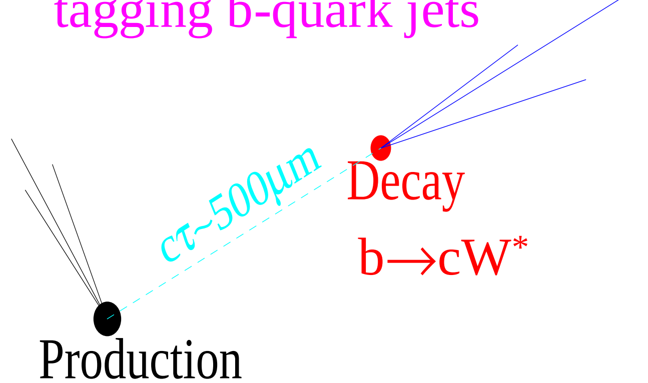
- central detector
  - drift chambers
  - transition radiation detector
- calorimeter
  - U-liquid Ar
  - uniform, hermetic
- muon spectrometer

Silicon Vertex Detector

The development of the silicon detector represents one of the greatest advance in detector technology



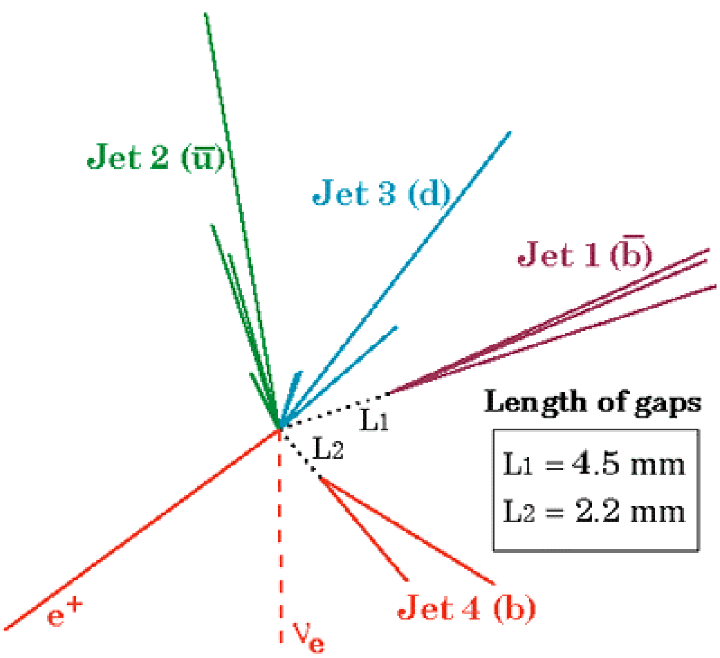
Powerful tool for tagging b-quark jets



$p + \bar{p} \longrightarrow t + \bar{t}$

$t \longrightarrow b + W^+$ $\quad$ $W^+ \longrightarrow e^+ + \nu_e$

$\bar{t} \longrightarrow \bar{b} + W^-$ $\quad$ $W^- \longrightarrow \bar{u} + d$



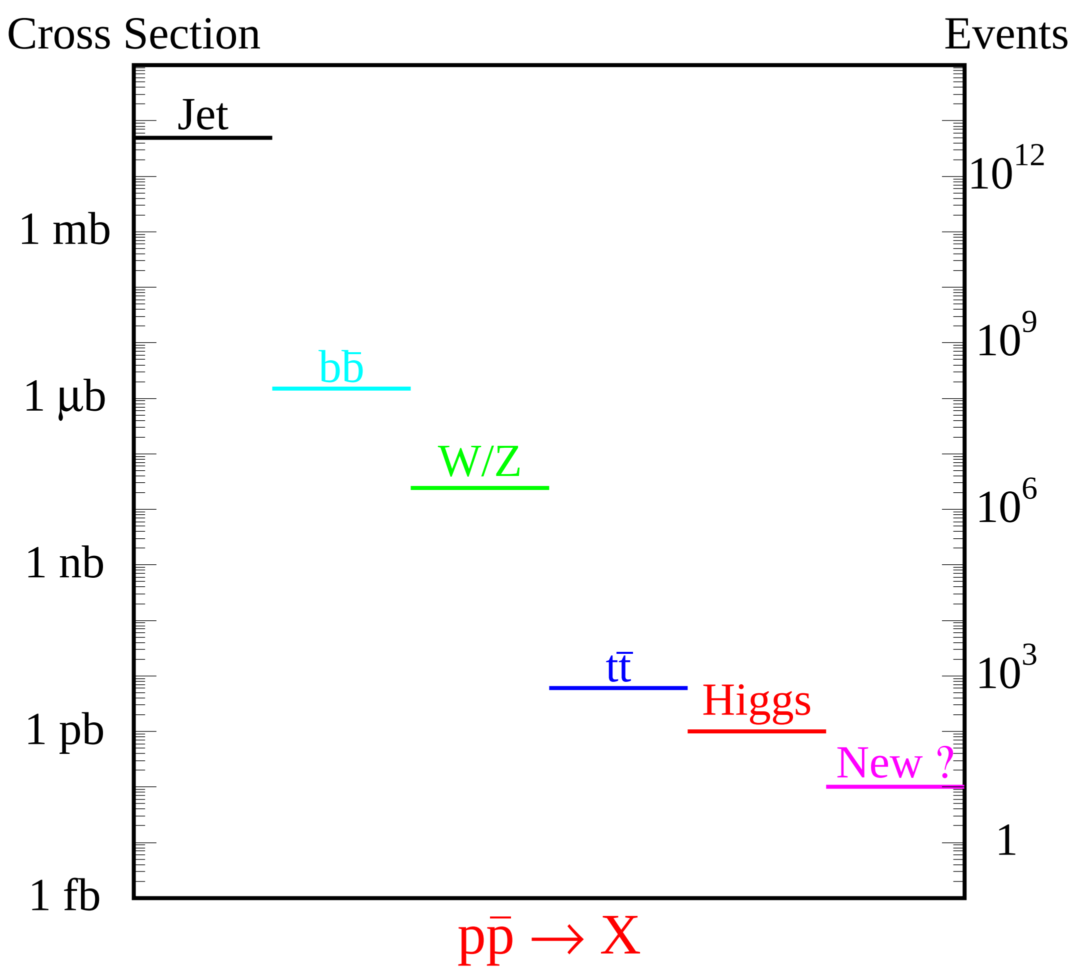
A CDF $t\bar{t}$ candidate

Both b-quark jets are tagged by their decay vertices

The event gives $m_{top} = 170 \pm 10$ GeV

Typical Cross Sections

The cross section is dominated by jet production.



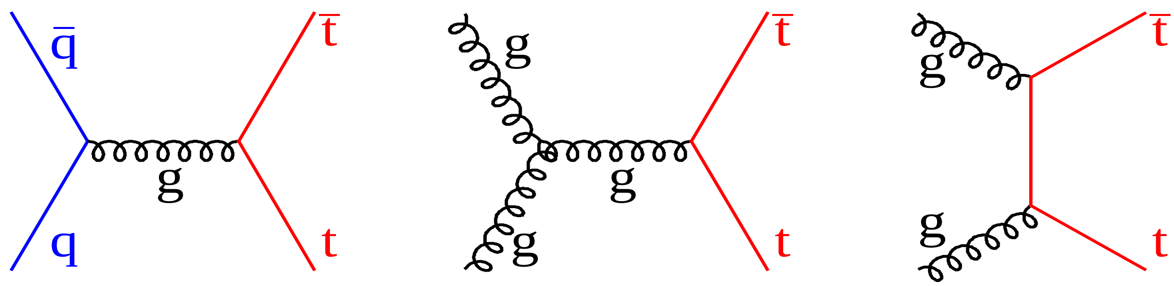
Interesting high p_T events are buried in huge backgrounds

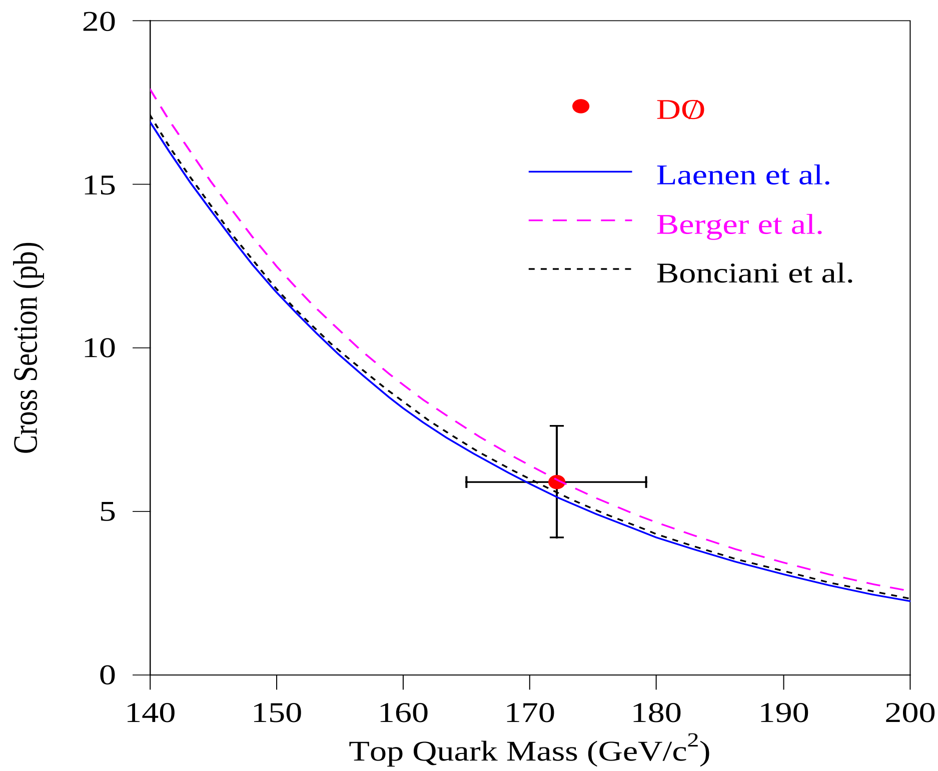
One of the challenges is to reduce backgrounds to acceptable levels through successive hardware and software algorithms

Highlight of Run I Physics

- **Top quark physics**
  - Discovery of the top quark
  - measurement of cross section and mass
  - study of top quark decay properties
  - search for single top production
- **Electroweak physics**
  - W/Z cross section and pT distributions
  - measurement of W boson mass
  - triple gauge boson couplings
- **Quantum Chromodynamics**
  - Jet physics
  - color coherence
  - small x physics
- **Searches for new phenomena**
  - searches for supersymmetry
  - searches for leptoquarks, compositeness etc
- **B physics**
  - inclusive b-quark production
  - B hadron lifetime measurements
  - B hadron spectroscopy
  - CP violation

Top Quark Discovery





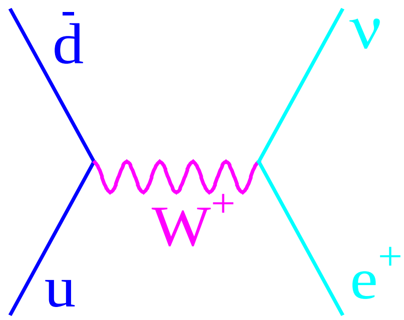
Based on a sample of ~ 39 (+41) $t\bar{t}$ candidate events

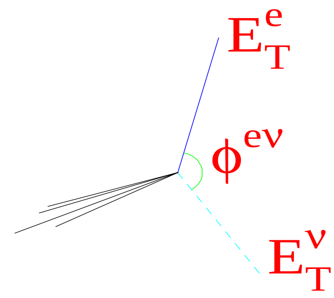
$$m_t = 172.1 \pm 7.1 \text{ GeV}$$

$$\sigma(p\bar{p} \to t\bar{t} + X) = 5.9 \pm 1.7 \text{ pb}$$

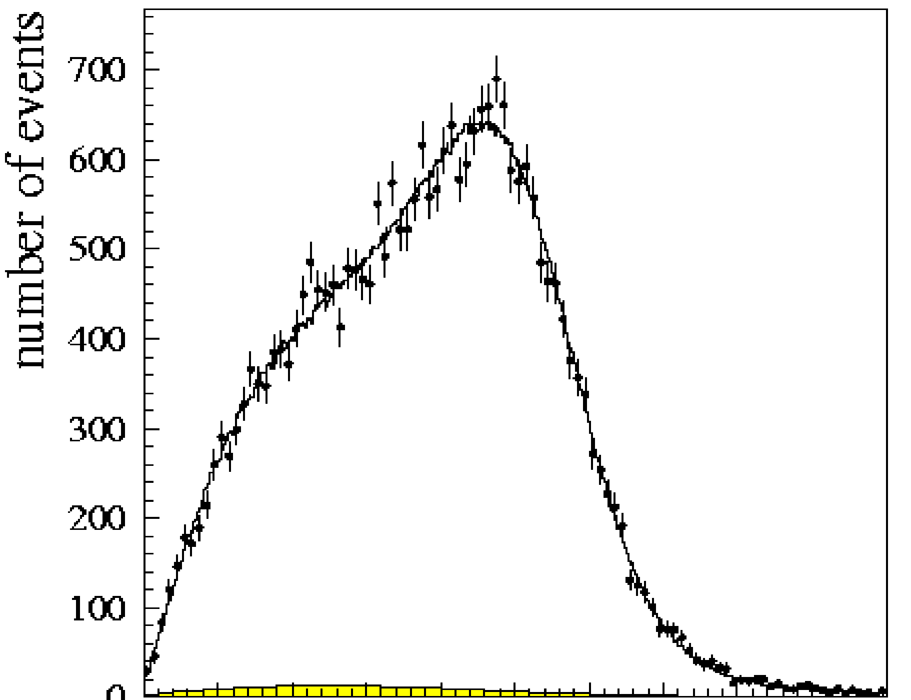
Measured cross section is in good agreement with all three Next-Leading-Order calculations

W Boson Mass





Transverse mass $m_T = \sqrt{2E_T^e E_T^\nu (1 - \cos\phi^{e\nu})}$



M_W = 80.48 ± 0.09 GeV/c^2

Phys. Rev. Lett. 80, 3008 (1998)

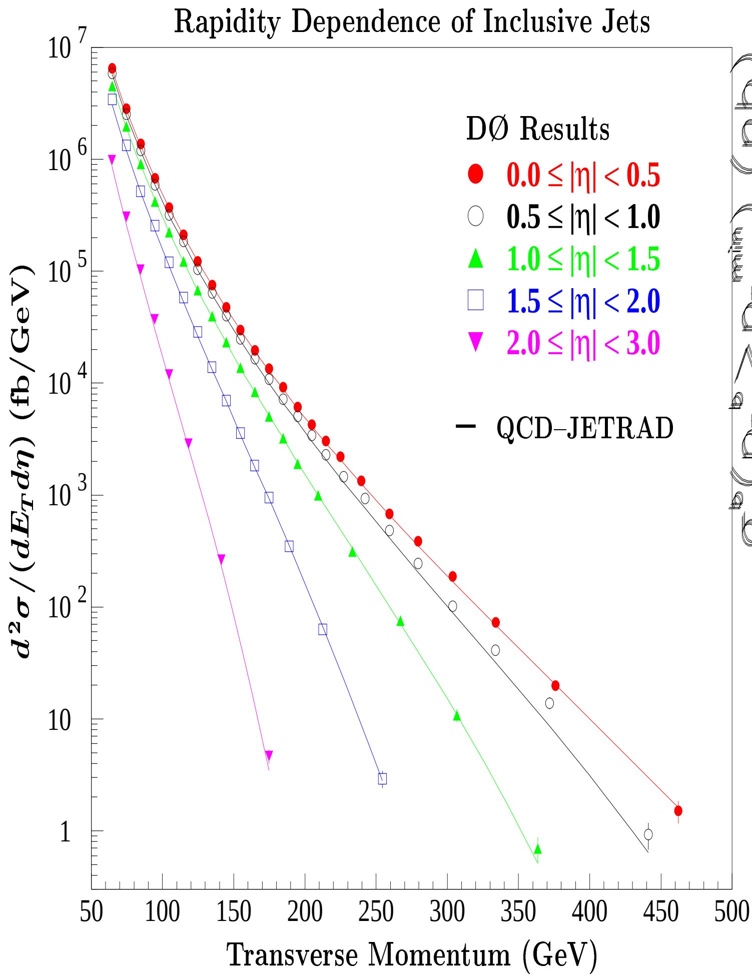
The error is presently dominated by statistics

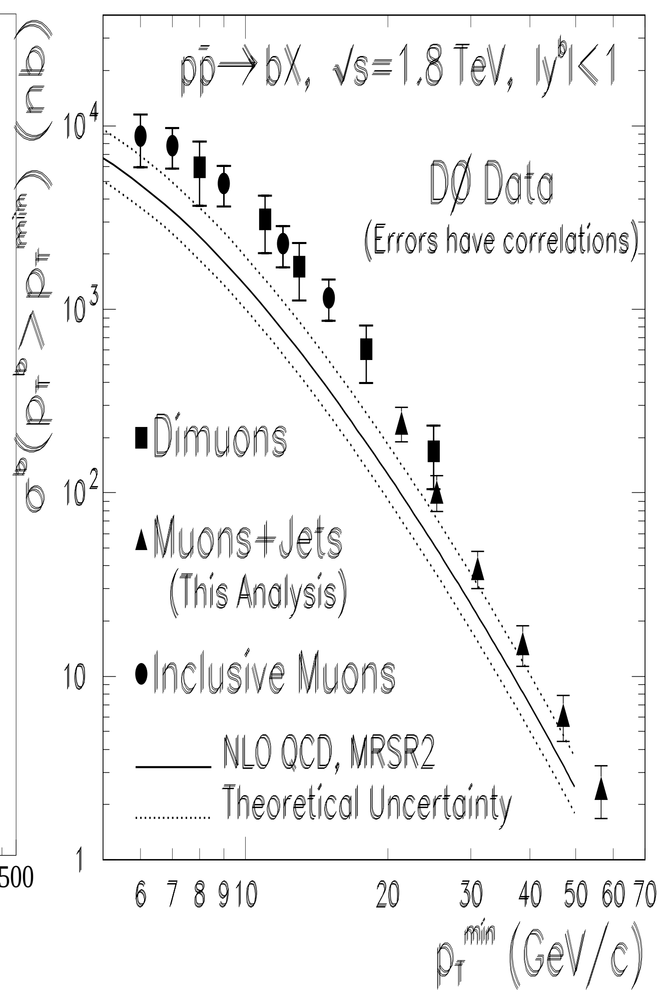
Jet Cross Section

Jets are copiously produced at hadron colliders

Test of QCD is limited by uncertainties in
- **theoretical calculations**
- **parton distribution functions**
- **jet energy scale**

One result of particular interest is the b-quark cross section measurements which indicate that NLO calculations underestimate the rates by a factor of 2.5



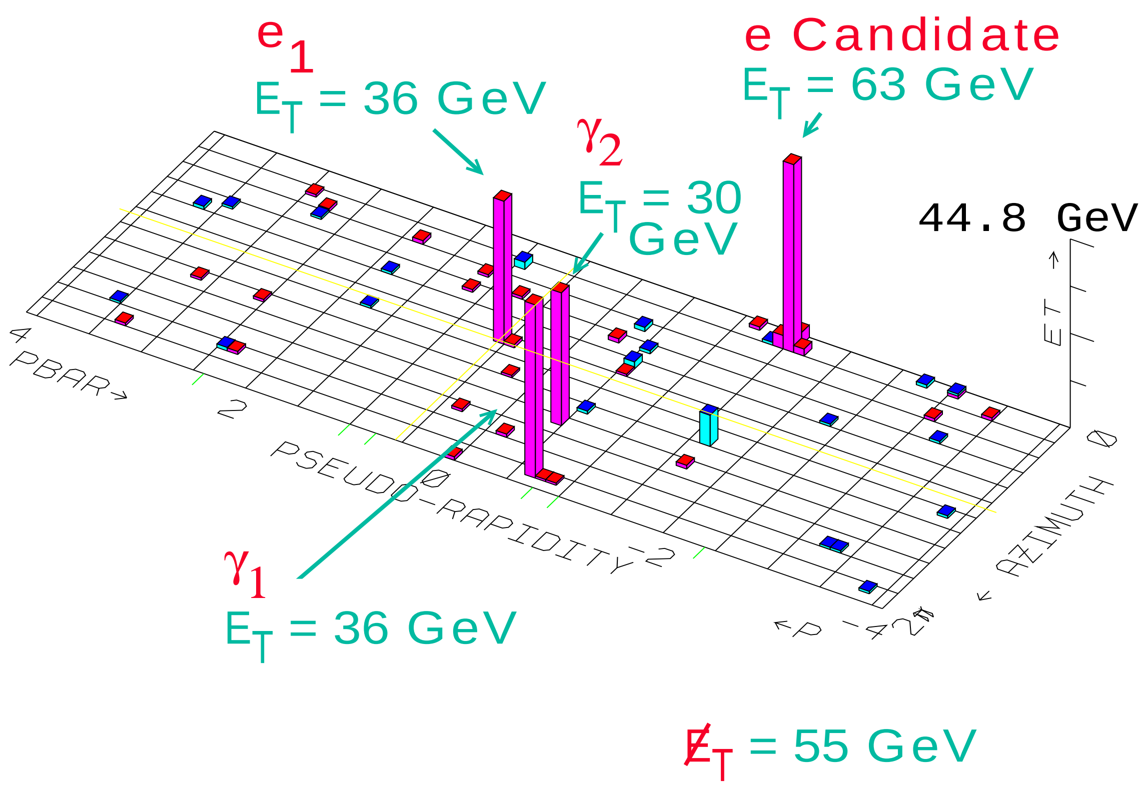


Search for New Physics

Much publicity has accompanied the CDF event.

It is unusual because isolated leptons, photons, and especially large missing E_T are rare in the Standard Model

$ee\gamma\gamma\not{E}_T$ Candidate Event

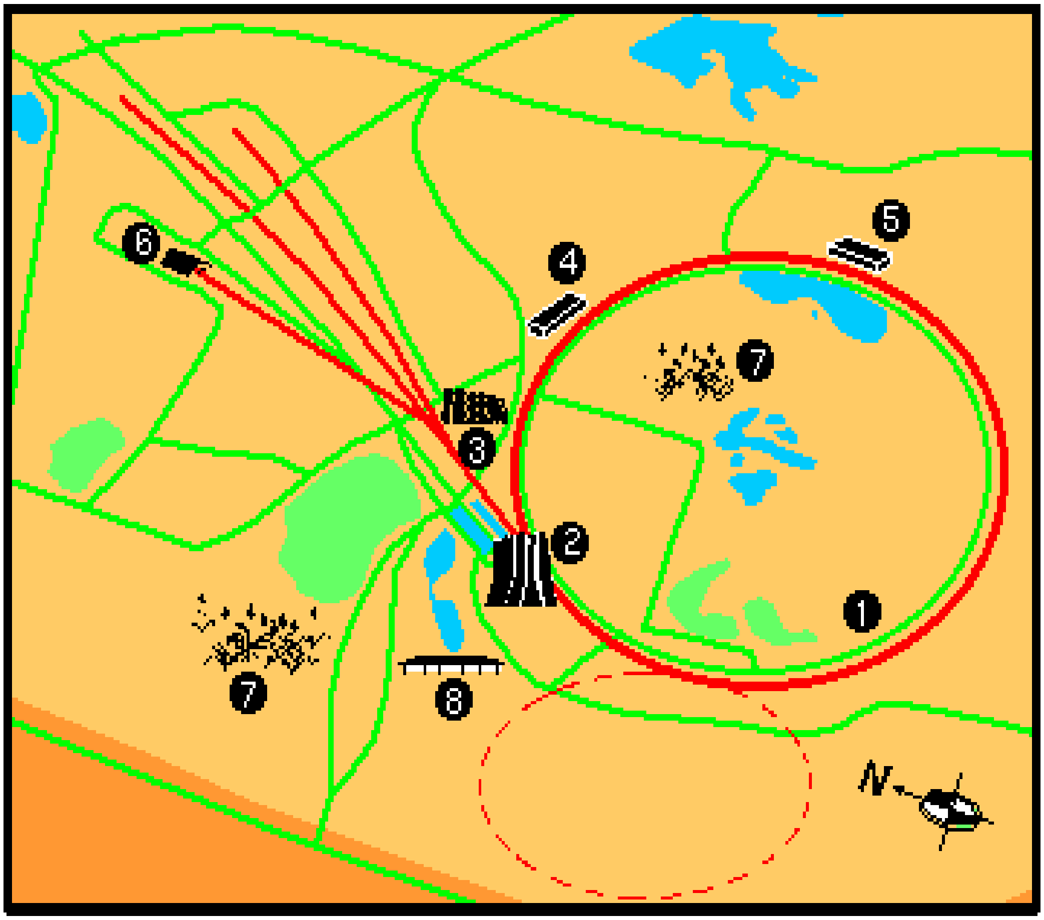


The probability for the event to be resulted from known process is estimated to be 10^{-6}.

Phys. Rev. Lett. 81, 1791 (1998)

It generated considerable theoretical interest

Tevatron Upgrade



Major Tevatron Improvements

1) Replace main ring with main injector
2) Construct a new anti-proton storage ring
3) Collider center-of-mass energy of ~2 TeV

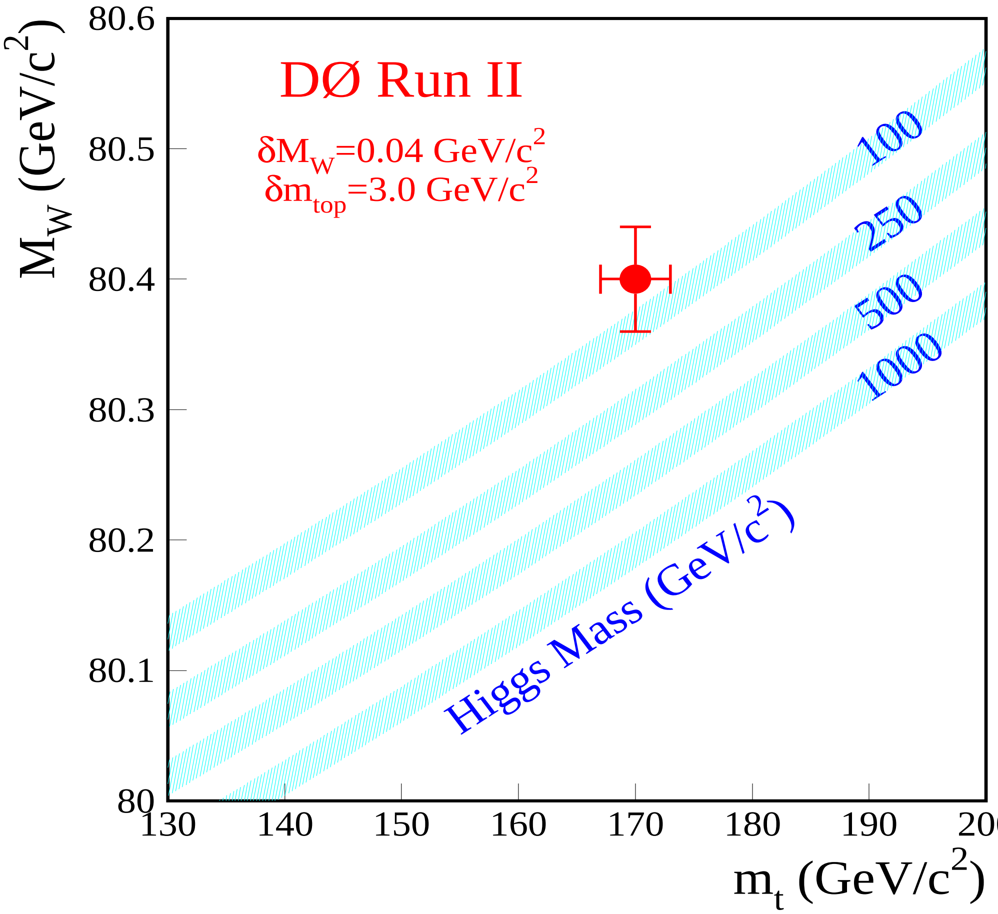
The machine will operate with 36x36 bunches (396 ns) initially and with 140x121 bunches (132 ns) eventually.

Run II machine goals:

1) Run IIa to achieve a luminosity of 5×10^{31} $cm^{-2}s^{-1}$ and an integrated luminosity of 2 fb^{-1}
2) Run IIb to achieve a luminosity of 2×10^{32} $cm^{-2}s^{-1}$ and an integrated luminosity of ~20 fb^{-1}

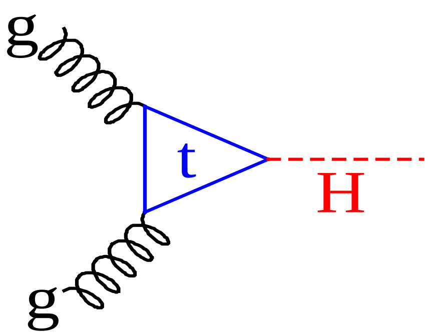
Top and W Mass

- **Statistical and systematic errors contribute equally to the total errors of the present measurements**
- **Most of the errors are expected to scale with $1/\sqrt{N}$, expectation:** $\delta m_t \Rightarrow$ **< 3 GeV**
  $\delta M_W \Rightarrow$ **< 40 MeV**



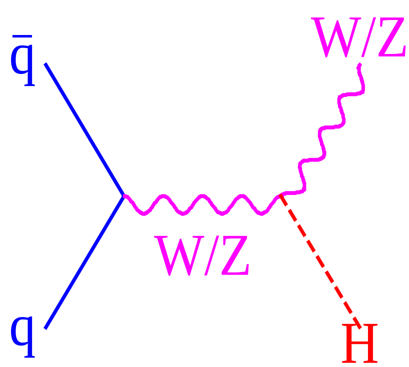
Combined with the data from LEP/SLC, the Higgs mass can be constrained to be within 30%

Higgs Boson Production

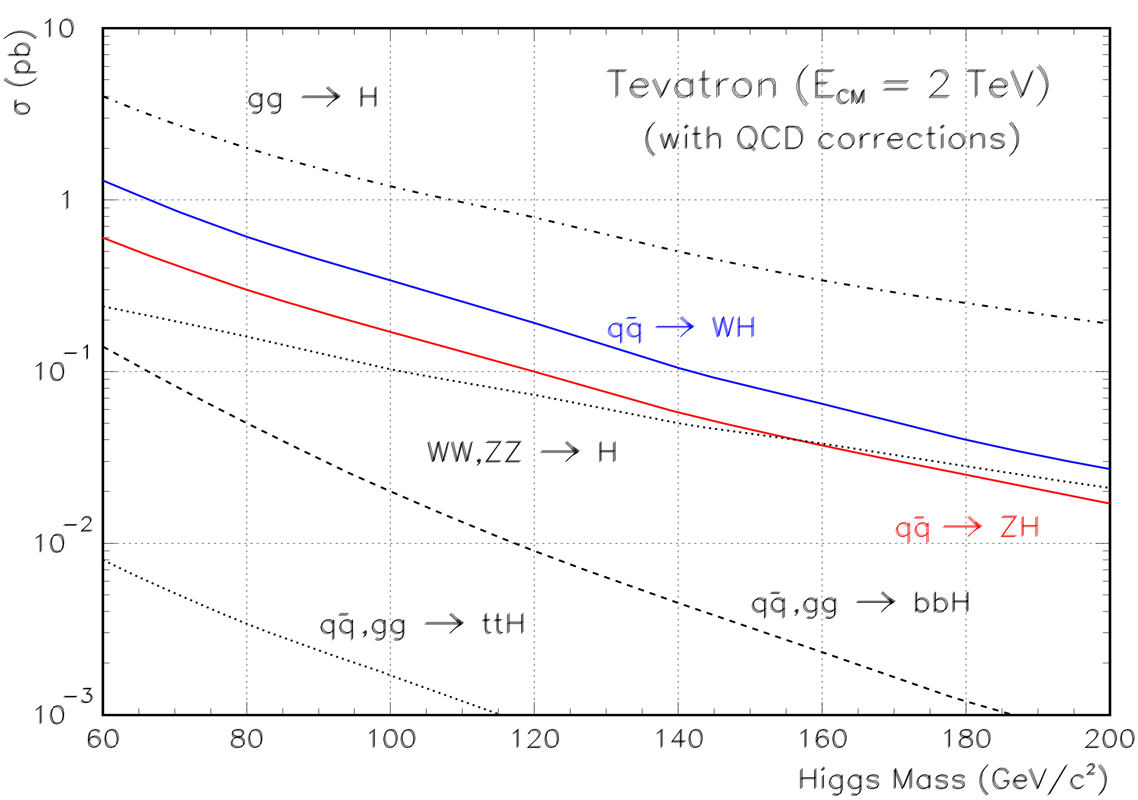


At Tevatron collider, the dominant process for Higgs production is through gluon - gluon fusion $gg \rightarrow H$

However, it has huge SM backgrounds
SM $b\bar{b}$ production for $H \rightarrow bb$ and
SM W^+W^- production for $H \rightarrow W^+W^-$



WH and ZH production modes have relatively smaller backgrounds

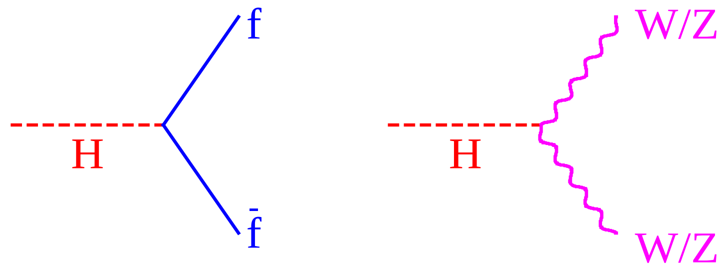


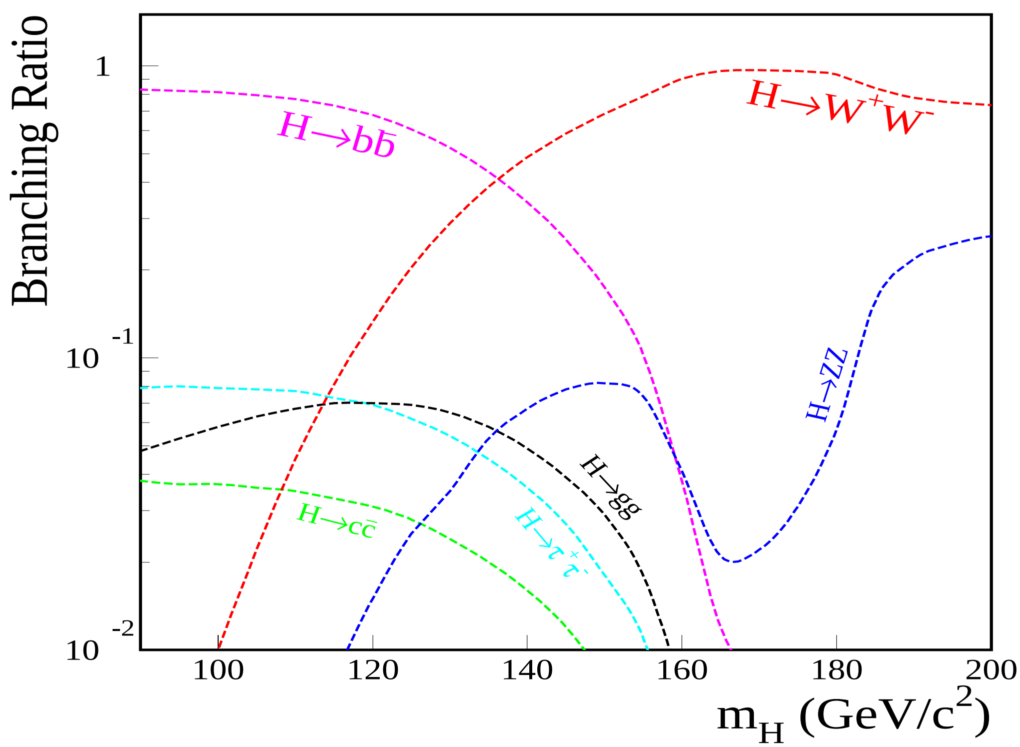
Higgs Boson Decay

Whenever the kinematics allows, the Higgs boson tends to decay into heavy particles

If $M_H < 120\,\mathrm{GeV}/c^2$, $H \rightarrow b\bar{b}$ dominates
$\Rightarrow$ SM background: QCD $b\bar{b}$ production

If $M_H > 140\,\mathrm{GeV}/c^2$, $H \rightarrow W^+W^-$ dominates
$\Rightarrow$ SM background: direct W^+W^- production





Higgs Search at Tevatron

LEP2 has excluded a SM Higgs boson with Mass less than ~ 114 GeV/c²

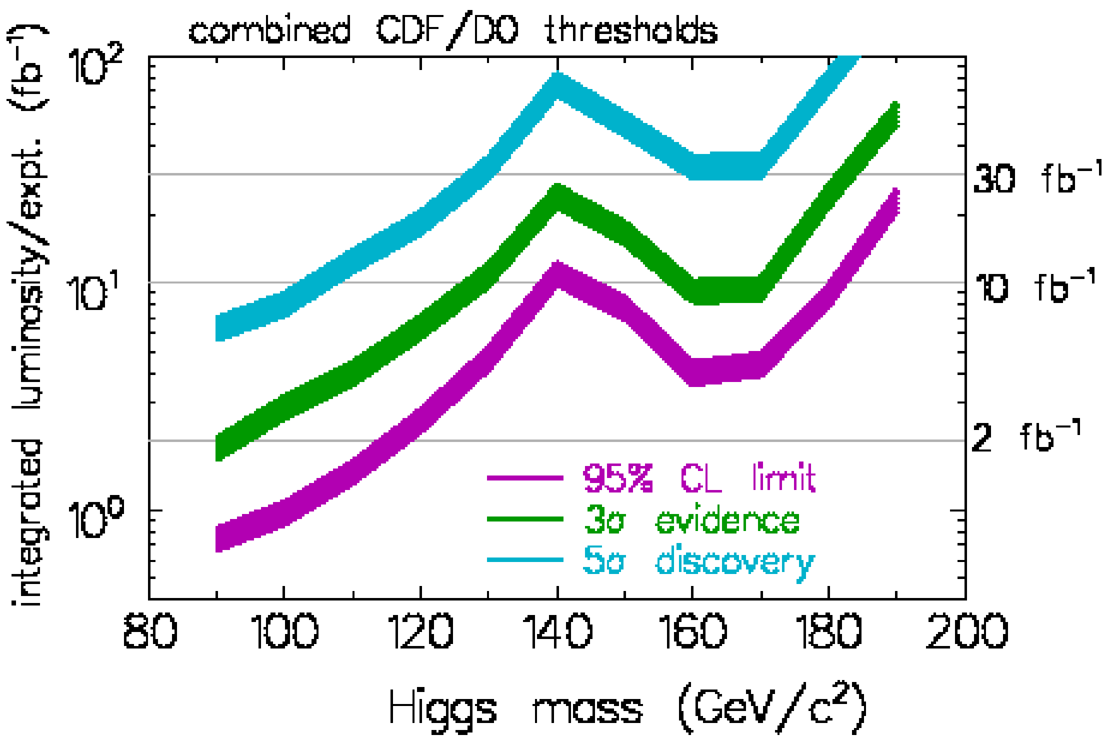
Some even claimed that LEP2 has seen a 115 GeV/ c² SM Higgs bosons

Higgs Search at Tevatron

$\mathrm{WH, ZH\ with\ H \rightarrow b\bar{b}\ if\ m_H < 120\ GeV/c^2}$

$\mathrm{WH, ZH\ with\ H \rightarrow WW^*\ if\ m_H > 120\ GeV/c^2}$

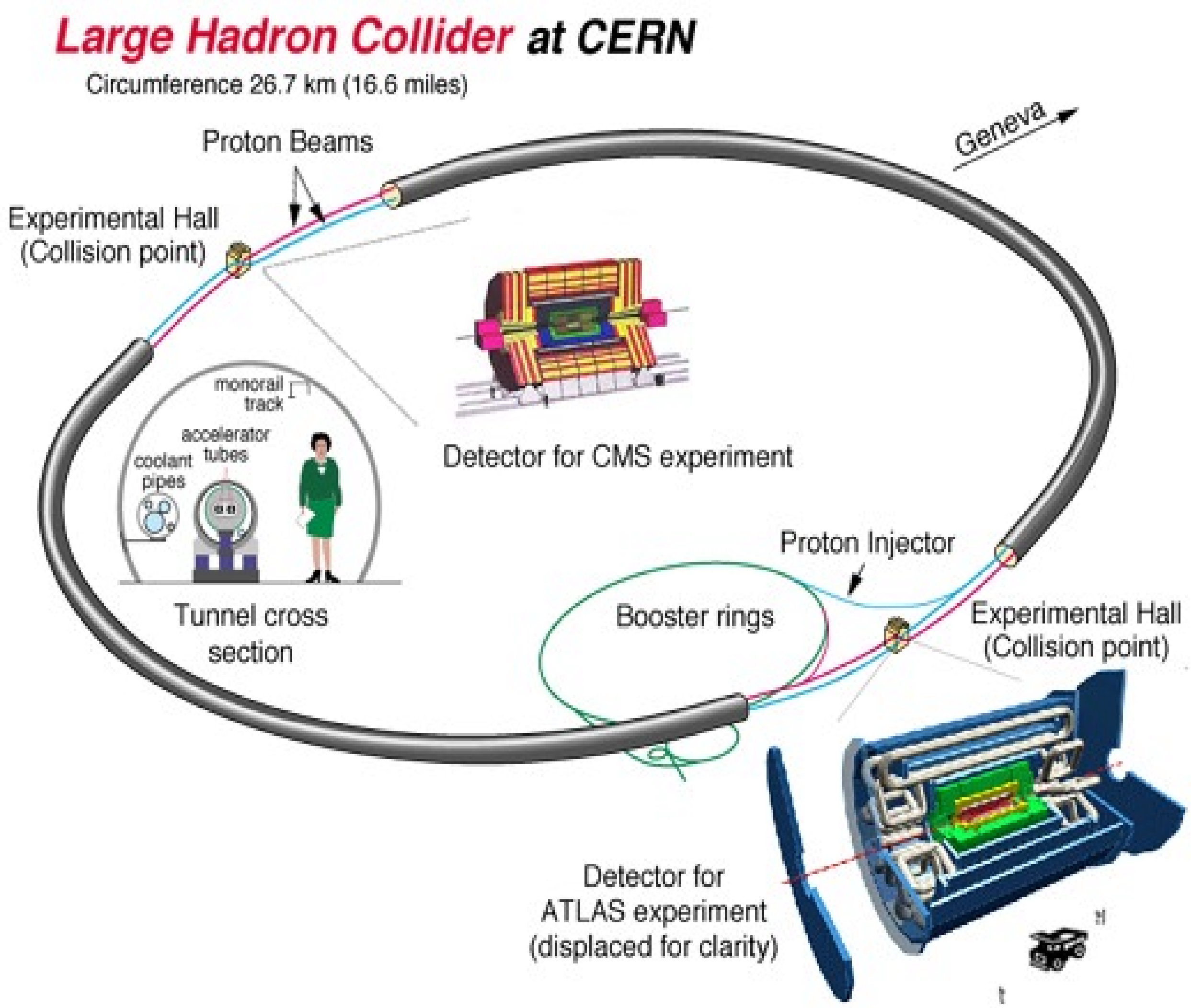
$\mathrm{gg \rightarrow H\ with\ H \rightarrow WW^*\ if\ m_H > 140\ GeV/c^2}$



Run 2b has a realistic chance for discovering or excluding the SM Higgs boson up to 180 GeV/c²

Large Hadron Collider

The Large Hadron Collider currently under construction at CERN is scheduled to start operating around 2005 with a center-of-mass energy of 14 TeV.

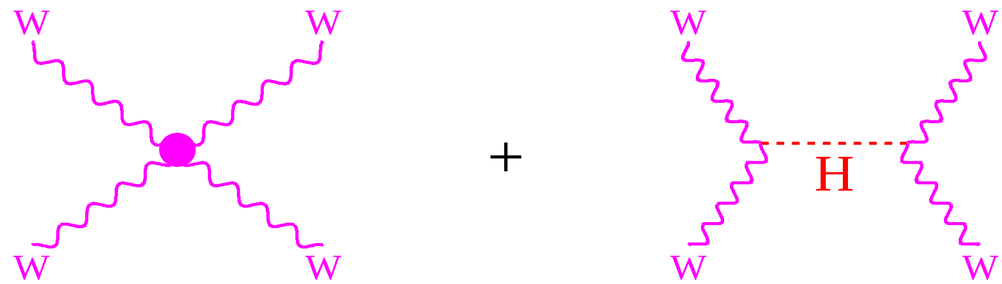


It is our great hope for exploring the TeV scale physics and understanding the puzzle of EW symmetry breaking.

What if there is no Higgs

Not only the Higgs boson is needed for particle masses, it is also needed to make

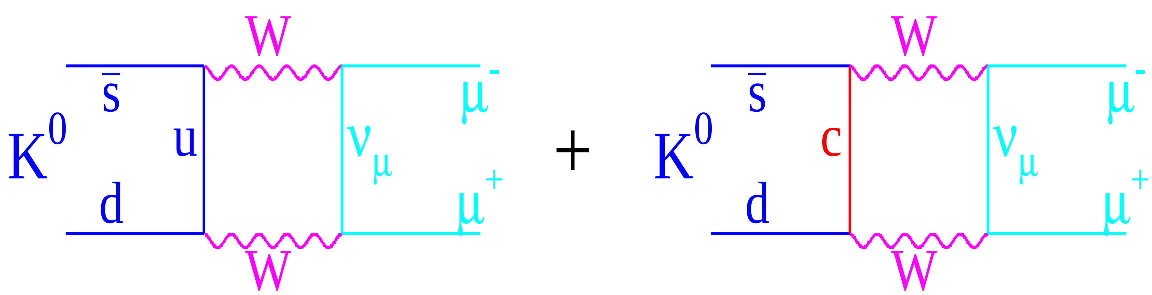
$$\sigma\left(W_L^+ W_L^- \rightarrow W_L^+ W_L^-\right) \text{ finite}$$



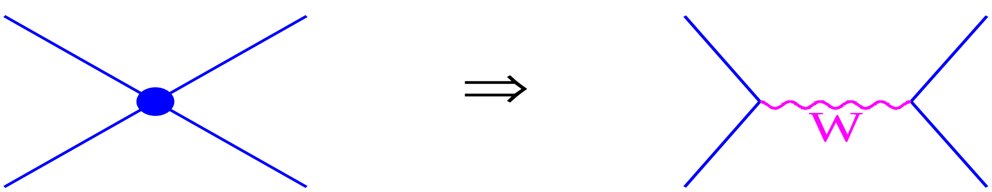
If the Higgs boson does not show up, we expect to see anomaly in WW→WW cross section

Historical Precedent

Charm quark was first postulated to solve $K^0 \rightarrow \mu\mu$ problem



W boson was introduced to make $\sigma(e\nu_e \rightarrow e\nu_e)$ finite



$$\sigma \Rightarrow \frac{G_F^2\, s}{\pi} \qquad\qquad \sigma \Rightarrow \frac{G_F^2\, M_W^2}{\pi}$$

Future Prospect

- Hadron colliders served us well in our pursue of high p_T, high mass physics
- The upgraded Tevatron and the new LHC will open up new domains of high energy exploration

What might we learn in the next decade?

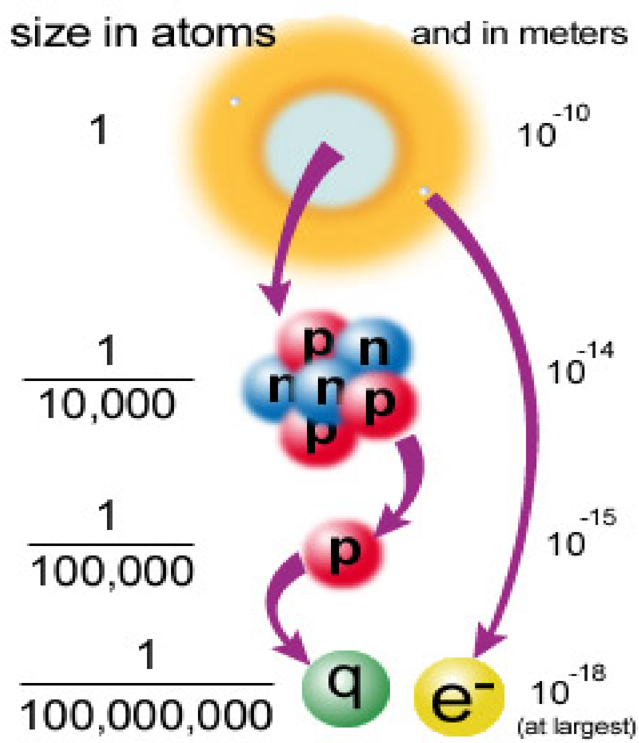
- Learn a great deal about top quark and from top quark
- Hope to unravel the puzzle of electroweak symmetry breaking
- First taste of supersymmetry?

Expect for unexpected

Basic Questions

What is the world made of ?

After a long journey, physicists have come to realize that the matter of the world is made from a few 'fundamental' building blocks of nature

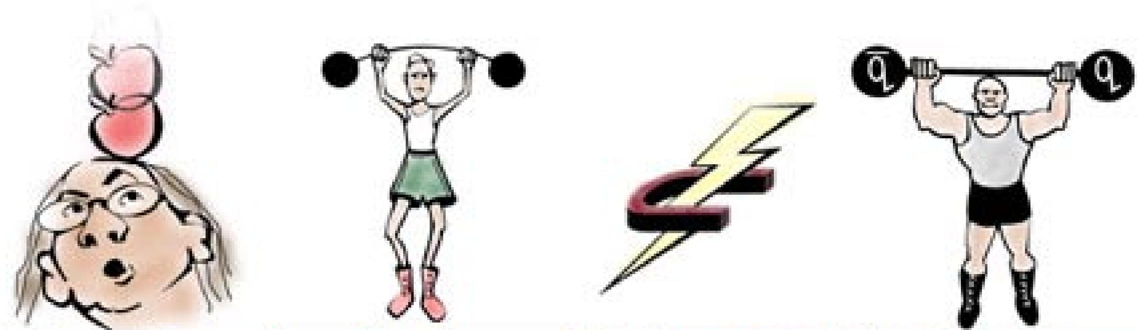


What holds it together ?

All forces in the world can be attributed to:

1) **Gravity interaction**
2) **Electromagnetic interaction**
3) **Weak interaction**
4) **Strong interaction**

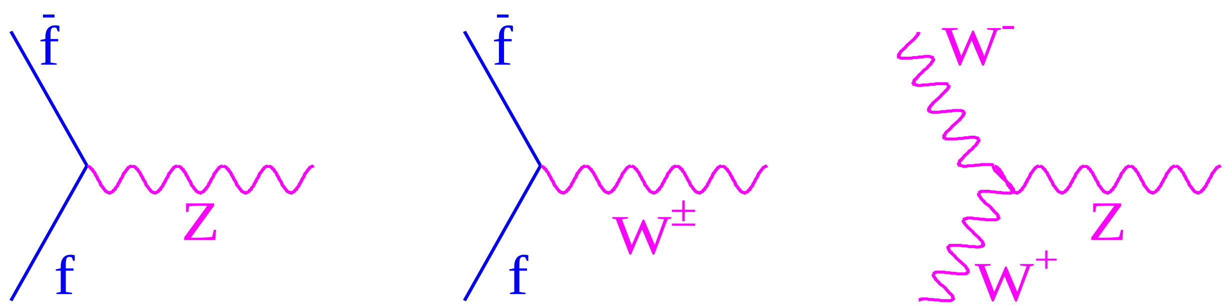
Fundamental Forces



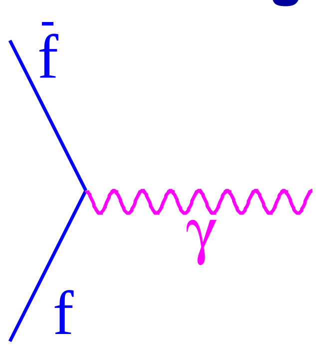
	Gravity	Weak	Electromagnetic	Strong
		(Electroweak)		
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

Physicists' view of forces

Weak forces



Electromagnetic



Strong